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OBSERVATIONS ON SURFICIAL EROSIONAL PROCESSES WERE MADE ALONG THE STEEP COASTAL SLOPES OF CALVERT COUNTY, MARYLAND. MEASUREMENTS OF SURFICIAL EROSION RATES WERE MADE USING CATCHMENT PANS AND EROSION PINS. EXPERIMENTS WERE CONDUCTED TO MEASURE THE RELATIVE EFFECTS OF CHANGES IN SLOPE ANGLE, MATERIAL TYPE, AND AMOUNT OF VEGETATION

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Observations of Soil Wash on Steep, Unvegetated Slopes: Calvert County, Maryland

by

Joseph P. Schweitzer

An essay submitted to The Johns Hopkins University in conformity with the requirements for the degree of Master of Science

Baltimore, Maryland

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Abstract

Observations of surface erosion were made along the steep coastal cliffs of Calvert County, Maryland, in order to determine the contribution of these processes to the overall recession of the cliffs. Slope recession rates were measured with the use of erosion pins and sediment catchment basins. Pin observations were made over a 13 month period; the pans were used during the summer only. The combination of freeze-thaw and overland flow during the winter months produced the greatest erosion rates observed at the study site. Slope angle was found to have a measurable influence on soil wash. The number of freezing nights and the amount of overland flow were found to contribute to soil erosion. The slope erosion observed during the study period is within a factor of two of long-term recession rates obtained from a series of aerial photos dating back to 1938, indicating that the processes observed have been acting on the slopes in the past.

1. Introduction

Observations of soil wash were made from February 1992 to March 1993 on steep coastal slopes in Calvert County, Maryland. This work is part of a larger project (Calvert County Slope Erosion Study-CCSEP) designed to determine the dominant erosion processes acting on these rapidly eroding cliffs.

Slope erosion occurs by a variety of processes which can be broadly divided into surface and subsurface mechanisms. This essay focuses on surficial erosional processes. Along the cliffs in Calvert County, surface erosion occurs by two primary mechanisms: freeze-thaw and surface wash by overland flow. One goal of this work was to measure rates of surface erosion mechanisms in the context of a larger project to determine the dominant erosion mechanisms--surface or subsurface--acting on the cliffs. Direct measurements of both types of erosion provide the basis for identifying dominant erosion mechanisms, their controls, and rates. A second goal was to investigate the variation in surface erosion with several factors that can control erosion rates. This provides a stronger basis for comparing erosion rates observed at Calvert Cliffs with those at other locations.

Surface erosion rates are difficult to observe or estimate; an idea of even the order of magnitude requires some direct observation. Larger scale rotational or shallow slides are much more noticeable and rare. Their volume can be more readily estimated and their importance can be overestimated even by a

careful observer. Surface erosion usually takes place with little transformation in the appearance of the slope face and proceeds by much slower, but much more frequent, or continuous action. The magnitudes of surficial and subsurface erosion can be comparable. To better understand overall cliff erosion requires that some estimate be made of the rates of all possible erosion mechanisms.

There is a large body of scientific work concerning soil wash by overland flow and freeze-thaw (Lawler, 1985; Evans, 1980). Application of these results to specific locations is difficult for several reasons. Soil loss relations are empirical, with fitted coefficients and exponents particular to the soil type, slope geometry and hydrologic conditions relevant to individual locations. Most literature concerning soil loss due to overland flow is limited to much more gentle slopes than the steep, nearly vertical slopes of Calvert County. Similar problems exist for freeze-thaw. Predictions of soil loss at one site from studies at other sites is difficult because a small variation in grain size or groundwater conditions can result in a large variation in sediment yield. The discussion portion of this paper addresses the issue of predictability in greater detail.

2. Field Methods and Observations

Sediment yield from steep slopes depends on slope angle, flux of overland flow, length of slope, amount of vegetation, and material properties such as soil moisture content, cohesion, and

grain size. A field site was chosen to examine the effects on erosion rate of slope angle, slope length, runoff discharge, and rilling. This was done by choosing measurable locations between which existed large changes in one control and much smaller variation in the others. Field studies were conducted along a 150 m stretch of cliff at Calvert Cliff State Park (CCSP) in Calvert County, Maryland (Fig. 1).

The experiment site is naturally divided into two sections: an extensively rilled section and one without rills. The rills were generally parallel to each other, approximately 25 cm wide and 10 cm deep. The slope angle varied between the two sections, with the rilled slope at 46^o and the non-rilled slope face at approximately 63^o. The difference in slope angle may be attributable to the wave protection provided to the gentler slope by large boulders of ironstone derived from beds above the experiment site. Neither slope is visibly undercut by waves, although wave activity is sufficient to remove slope debris from the toe. One may presume that erosion of intact material and removal of weathered material from the slope toe proceeds more rapidly along the steeper, unprotected slope. Profiles of the lower portions of both the rilled and non-rilled slopes are given in Figure 2 (bluff top elevation is approximately 16 m above NGVD).

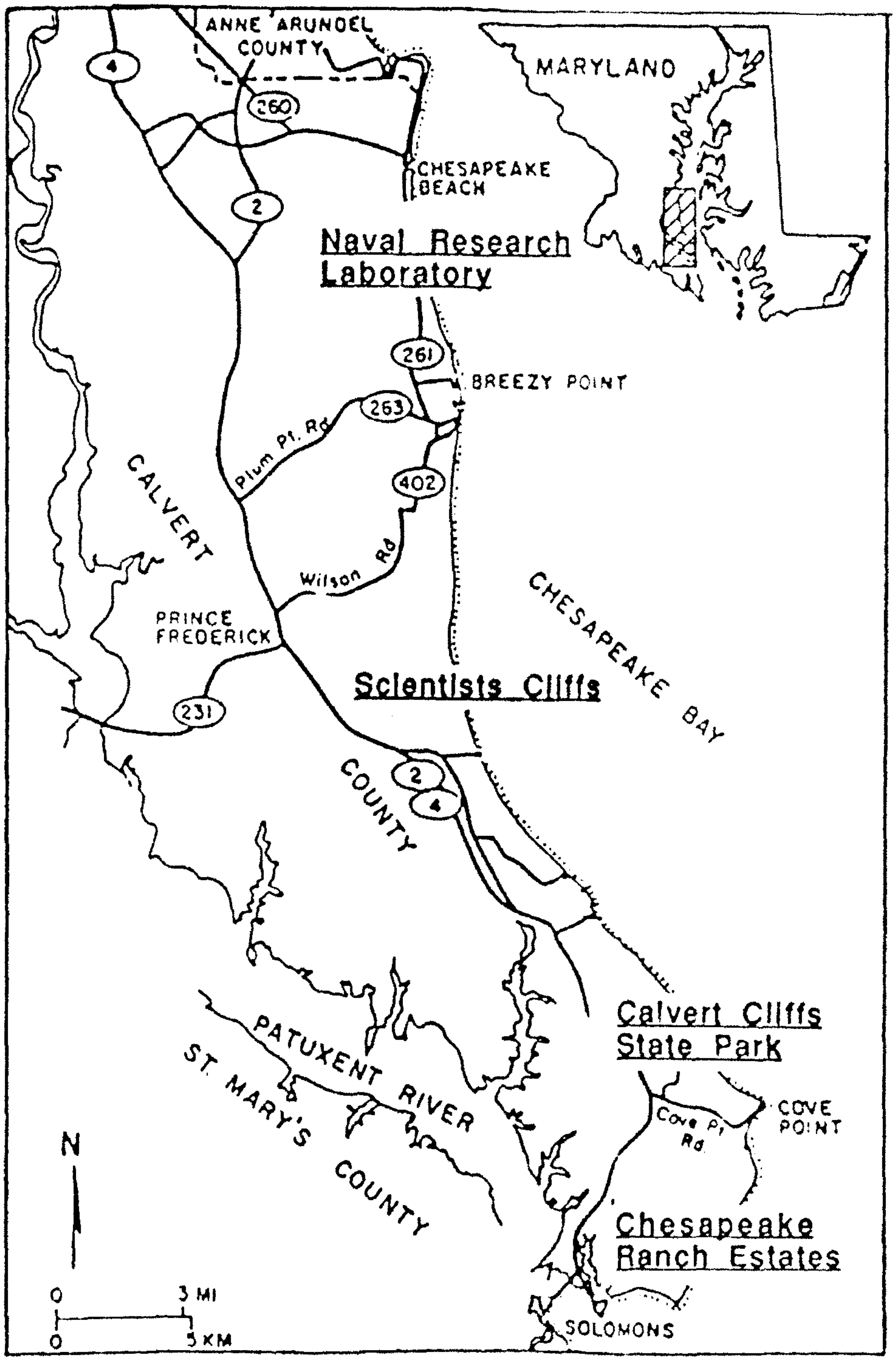


Fig. 1 Experiment Site Location in Calvert County, Maryland

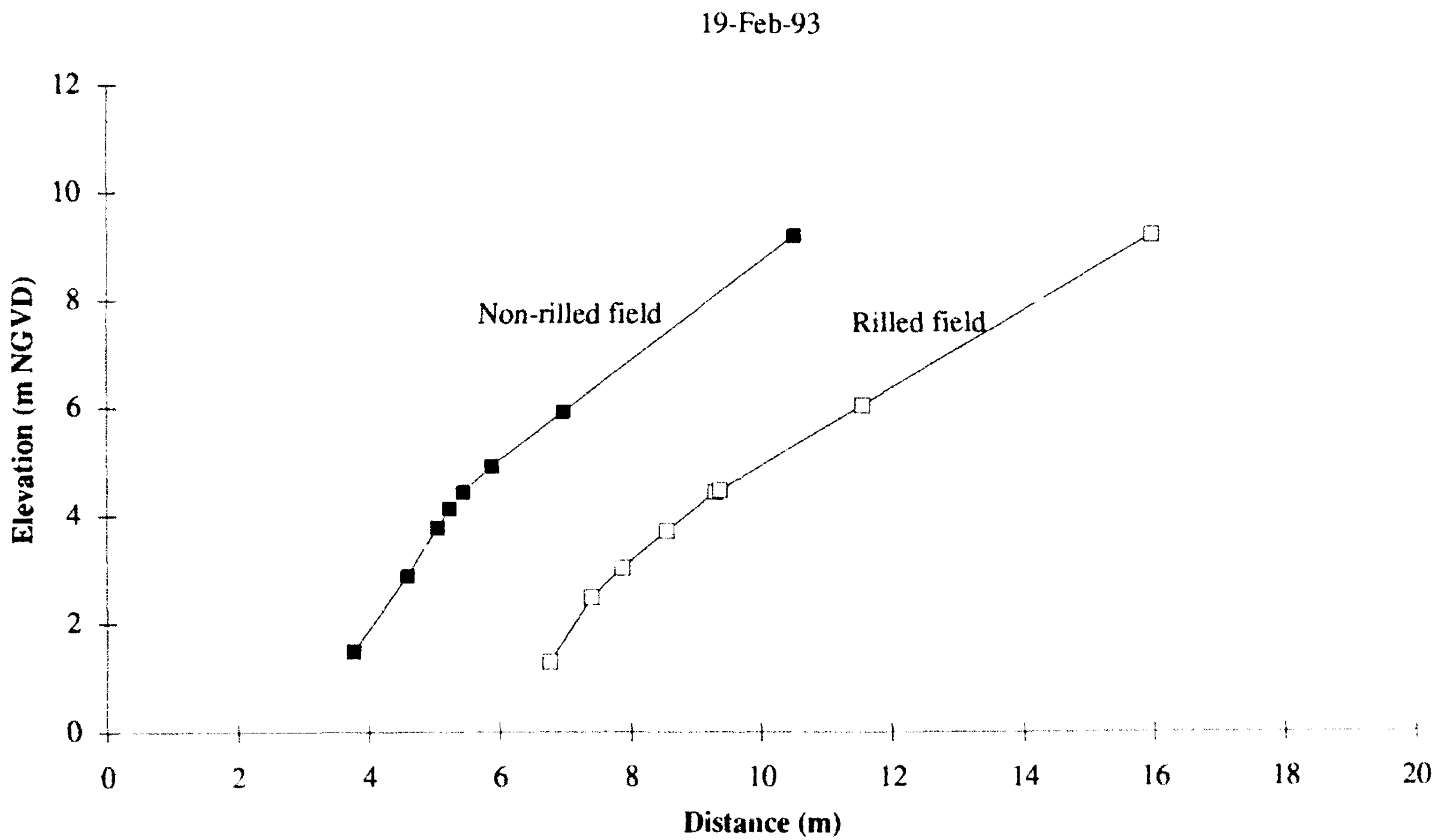


Fig. 2 Slope Profiles of the Lower Portions of the Erosion Pin and Pan Fields

The study sections are composed of sedimentary beds in the St. Mary's formation just below its contact with the Choptank Formation. Both formations were deposited in very shallow shelf to marginal marine environments (Olson et al. 1988). The upper St. Mary's formation has an age of 10.4 million years and is characterized as relatively undeformed and unlithified marine, terrigenous silts, sands, and clays (Kidwell, 1984). The sedimentary bed in which the measurements were made is a slightly moist, gray, clayey silt with traces of fine sand (44% clay, 44% silt, and 10% fine sand).

Erosion was measured by collecting sediment and water runoff in pans mounted flush to the slope and by observing slope recession relative to iron pins driven in to the slope. The pans and pins were located in four fields across representative sections of both the 46° and 63° slopes. The general site layout is given in Figure 3. Two pin fields were located on the borders of the CCSP experiment site: One was located in the rilled, 46° portion of the slope while the other was in the non-rilled, 63° section. Pans were located in the center of the experiment site but covered both sections.

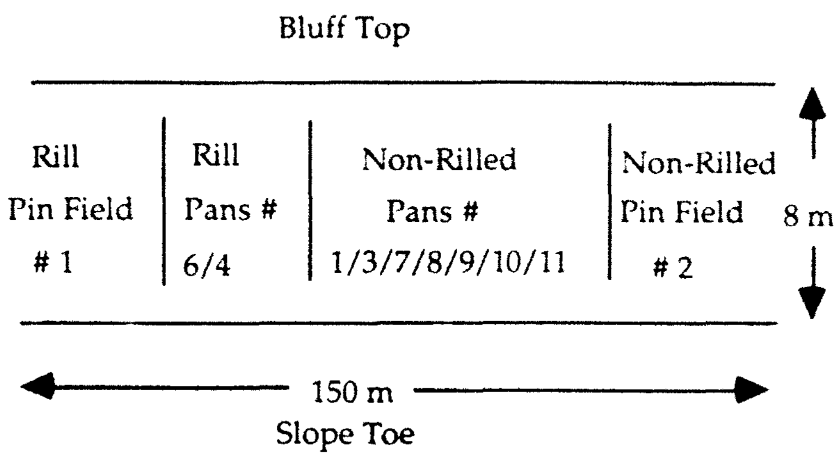


Figure 3 Experiment Site Layout.

2.1 Pan Measurements

To measure sediment yield from overland flow, a means of capturing both sediment and surface runoff was needed. Many existing techniques (Dunne and Aubrey, 1986; Mathier et al, 1989) are unsuitable for the steep slope angle and unlithified nature of the slope material at the study site. Sediment and water were collected during rainfall events using a catchment pan. The pans were constructed of plastic basins 33 cm long, 8 cm wide and 7 cm deep. The pan drained through a short section of 5 cm pipe into a large plastic bottle. Bottles could then be collected and replaced with empty ones without disrupting placement of the pans. The pipe was wide enough and the material sufficiently fine to allow the sediment to wash freely into the bottle without clogging. To ensure that all surface wash entered the pan, an aluminum sheet was inserted 2 to 3 cm into the slope face. Sides of the sheet were slightly raised and the entire surface was angled downward to direct all

surface wash into the pan. This sheet, or lip, was secured to the inside edge of the pan with glue and rivets. To minimize the amount of water captured in the pan from direct rainfall, an aluminum hood was attached to the downslope side of the pan and folded over the top of the entire pan and most of the lip (Fig. 4).

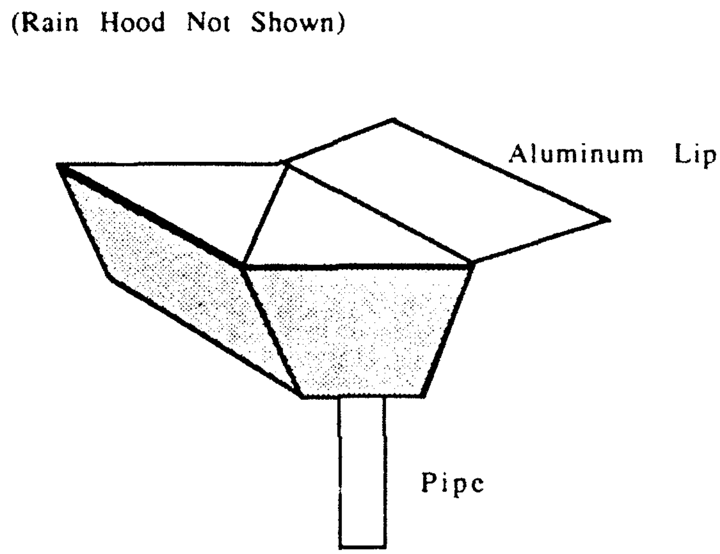


Fig. 4 Sediment Collection Pan

Pans were attached to the cliff face by two metal pins 0.95 cm in diameter and 60 cm long. Holes were drilled (not hammered) approximately 25 cm into the cliffs to minimize disturbance. Pins were pushed by hand into the holes and tapped an additional 5 cm with a hammer to ensure that they were secure. Each pan was then placed on top of the pins and secured with wire (Figs. 5 and 6).

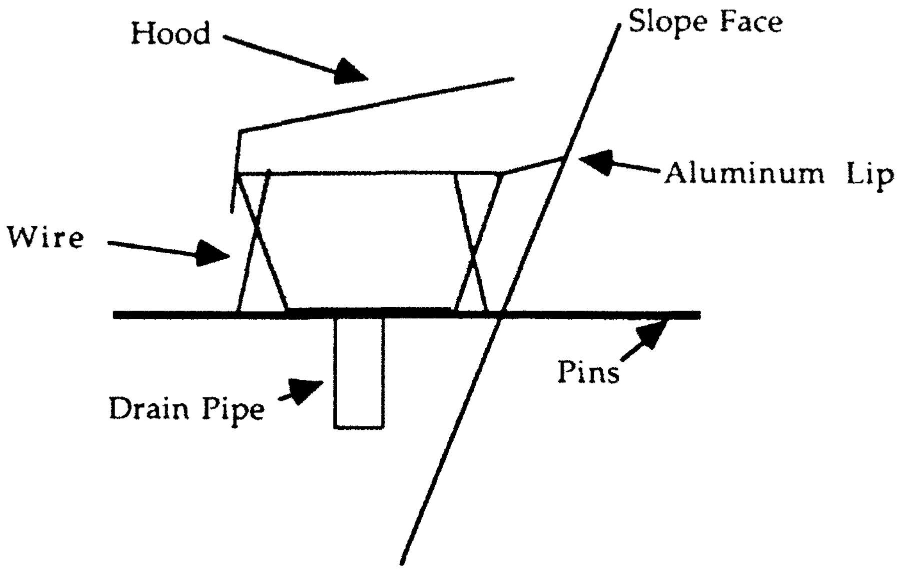


Fig. 5 Securing Pans to Slope Face (Side View)

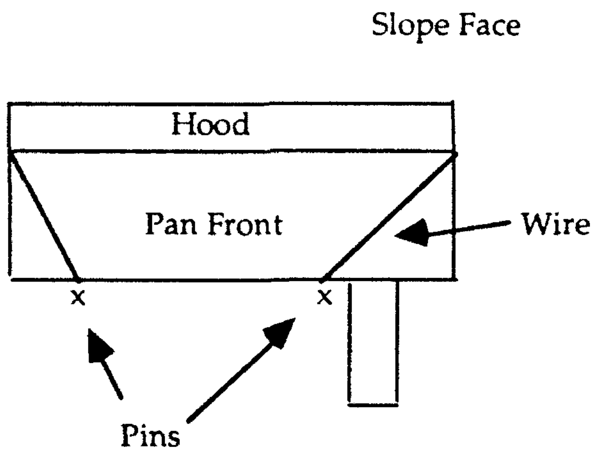


Fig. 6 Securing Pans to Slope Face (Front View)

The pan locations were selected to examine the effects of rilling, slope angle, and slope length above the pans. To examine the effects of rilling on sediment yield, seven pans were placed on the rilled and non-rilled portions of the slope. Three pans were located on the 46° slope, two of which

intercepted rills (#5, #6) while the third (#4) did not. For comparison, four pans (#1, #3, #10, #11) were located in the non-rilled portion of the slope. All seven pans were located at the same elevation with approximately 15 m of slope above each pan. All other controls of sediment yield (material type, percent moisture content, and vegetation) were constant. After the first rainstorm, pan #5 was abandoned due to difficulties in maintaining contact with the slope face. This left one pan intercepting a rill and one on the non-rilled portion of the 46° slope.

Location	Slope Degree	Elevation (m)	Rilled/ Non-Rilled	Slope Test	Rill Test
Pan #1	63	1.75	nonrilled	X	
Pan #3	63	1.75	nonrilled	X	
Pan #4	46	1.75	rilled	X	X
Pan #6	46	1.75	nonrilled		X
Pan #7	46	2.5	nonrilled		
Pan #8	63	1.75	nonrilled		
Pan #9	63	1	nonrilled		
Pan #10	63	1.75	nonrilled	X	
Pan #11	63	1.75	nonrilled	X	

Table 1 Pan Attributes

Sediment yield, and, when possible, overland flow were measured during eight convective storm events during July, August, and September of 1992. The pans were left in place between the rainstorm events and there was no measurable evidence of other surficial erosional processes (i.e., piping, seepage erosion, wind, etc.). Sediment yield results are presented in Figure 7. Sediment yield has been combined for three slope categories: non-rilled, 46° slope; rilled, 46° slope;

and non-rilled, 63° slope. A much greater sediment yield is observed for the rilled portion of the slope than for either non-rilled 46° and 63° slopes. Pans were kept in place from 27 July until 21 December 1992. The pans continued to collect sediment from 26 September to 2 December but were not checked after each separate rainfall event. The amount of sediment in each pan during this fall period represents the total yield over several months and is not used to individual rainfall events.

The original goal of the pan investigation was to measure both the sediment and water fluxes off the hillslope for each storm event. For reasons of safety (high tides, nearby lightening, etc.) or timing, it was possible to measure both sediment and water flux during three rainfall events. During all other rainfall events, only sediment yield was measured accurately. Table 1, Appendix A, lists the sediment yield, and when available, overland flow in each pan for all measured rainfall events.

Qualitative observations provide some insight into erosion rates due to overland flow. Even though nearby piezometer data confirmed that the lower slope was completely saturated, the moisture content of the material at the surface varied considerably. In between rainstorm events, the upper 2 to 5 cm of the slope surface would dry and crack, creating a weathered, friable exterior that was more susceptible to erosion than the smooth surface material. Generally, the longer the

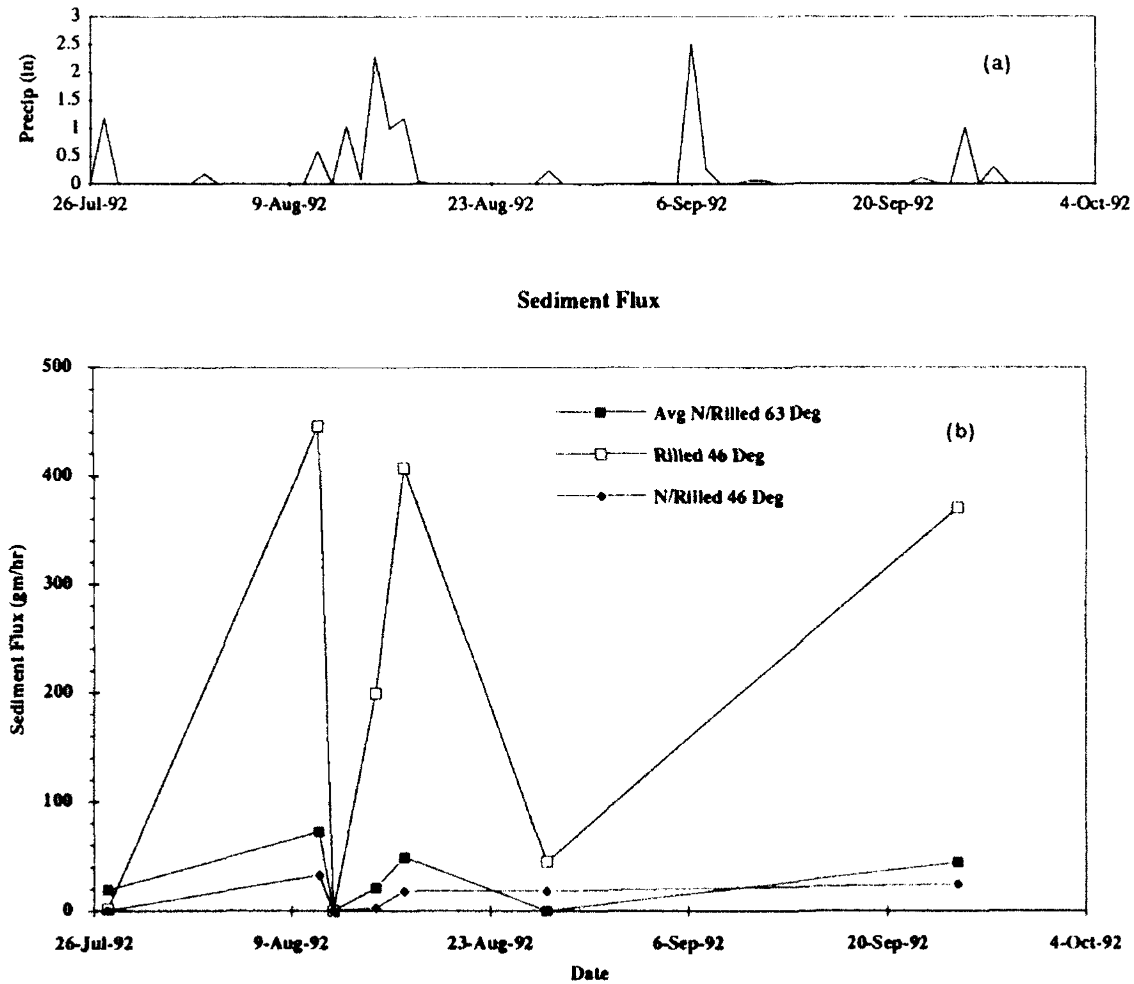


Fig. 7 (a) Total Daily Precipitation from PNAS; (b) Sediment Flux for Non-rilled 63 Deg, Rilled 46 Deg, and Non-rilled 46 Deg

interval between rainfall events, the more extensive the desiccation and weathering.

On the steeper, non-rilled portion of the slope, periodic waves of sediment were observed moving downslope. These waves generally took several storm events to travel down the entire slope face. This was not the case on the rilled portion of the slope face. Material in the interrill area was not *in situ* , but debris deposited from upslope. This overlying material gradually thickens downslope to a maximum depth of 20 cm. Because this material also has a very high clay content, it appears as cohesive as the *in situ* material when dry, but is much less cohesive when fully saturated. From observations, the majority of the sediment captured during rainfall events came from the material which comprises the interrill area.

2.2 Rainfall and Temperature Measurements

Rainfall data (amount, duration, intensity) was measured by two nearby automatic weather stations. One was located 3 km to the north at the Calvert County Nuclear Power Plant (CCNPP), the other was 8 km to the south at the Patuxent Naval Air Station (PNAS). One of the original goals of this study was to determine sediment yield as a function of precipitation. Because there was little agreement between these two stations for many of the rainstorms, it is difficult to accurately determine the total rainfall and intensity at the experiment site. Total rainfall and intensity could be accurately estimated at the

site when hydrograph records were similar between PNAS and CCNPP. Two rainstorm events had similar hydrographs and a third was confirmed with on site observations. Appendix B, graphs 1 through 11 provides a comparison of total rainfall and intensities for each of the storm events.

Because freeze-thaw is a function of temperature, air temperature measurements from Patuxent Naval Air Station were recorded for the months when freezing was possible. Maximum, minimum and mean temperature are listed in Appendix C, Tables 1 through 6.

2.3 Material Analyses

Material analyses were completed to convert weight of material to volume for comparisons between the two surficial erosional processes. Separate values for water and sediment were obtained from the surface wash by using a simple gravimetric procedure. Surface wash was poured into a graduated cylinder weighed and measured. Using density values of 2.6 gm/cm^3 for the sediment and 1.0 for water, values of each were calculated by:

$$M_s = \rho_s V_s = \rho_s \frac{M_t - \rho V_t}{(\rho_s - \rho)} \qquad (1)$$

and

$$M_{we} = \rho V_t = \text{mass water equivalent}$$

$$M_s = \frac{\rho_s}{\rho_s - \rho}(M_t - M_{we}) \qquad (2)$$

where: Mt = total mass
ρ = density of water
ρ_s = density of sediment
V_t = total volume of mix
V_s = volume of sediment

Bulk density was determined by inserting several metal cylinders of known volume into the slope and weighing the material. The wet bulk density was then computed by dividing the weight of the wet material by the volume of the cylinder. Four samples were taken at the CCSP site. Percent moisture content and dry density of the material were computed with similar calculations after the samples were oven-dried in an oven at 100 C° for 5 days. Dry weight permits a comparison of the pan data with the pin data. The bulk density of the *in situ* material allows for a conversion of the pan sediment mass into volume of slope material as measured by the pins.

Results of the calculations above provide values of:

Non-rilled slope:

Bulk density (wet): 1.79 gm/cm3
Bulk density (dry): 1.32 gm/cm3
Percent moisture content: 34.6%

Rilled slope:

Bulk density (wet): 1.75 gm/cm3
Bulk density (dry): 1.29 gm/cm3
Percent moisture content: 40.5%

The above calculations were made with thoroughly saturated material because most slope recession occurs when the material is saturated.

2.4 Pin Field Measurements

Objectives of the pin field experiments were two-fold: to directly measure slope recession over a relatively long period and to measure the influence of freeze-thaw on hillslope erosion by including winter observations.

Controls on erosion rate due to freeze-thaw are temperature, material properties, soil moisture content, time, and slope angle (Lawler, 1978). Temperature is further related to factors such as desiccation, frost activity, and temperatures of the soil and the air directly above the soil. The aspect of time includes the length of time of both freeze and thaw, as well as the frequency with which temperatures fluctuate about 0° Celsius. Pins were located so that variations in the controls on erosion by both freeze-thaw and overland flow could be observed.

The pins were placed in four separate clusters of simple geometric patterns. Others (Haigh, 1977) have experienced problems using of pins on steep slopes due to accelerated

erosion around the base of the pin as a result of improper emplacement and the pin acting as a temperature conduit during freeze-thaw episodes. Similar observations were not made at CCSP throughout the duration of this experiment. A total of 58 pins were installed during February 1992 with a total of 338 separate measurements being made until March 1993.

Steel pins (similar to those used to secure the pans to the slope face) were placed in holes drilled into the slope to minimize damage to the intact material. The pins were emplaced so that only 1/8 of the pin was exposed. Erosion was measured by taking periodic measurements of the exposed pin.

On the rilled portion of the slope face, 10 pins were placed along a single horizontal row spaced approximately 0.2 m apart. The pins were placed at the same elevation as the pans and crossed two complete rills (Fig. 8). On the non-rilled portion of the slope face, three rows of five pins were established with 1.5 m between each pin and 1.5 m between rows (Fig. 9). The center row was at the same elevation as the pans. During a storm event, floating debris in the bay struck the bottom row of pins and damaged them beyond use.

Rilled Slope

Bluff Top

	A	B	C	D	E	F	G	H	I	J
Row 1	.	.	.	.	.	.	.	.	.	.

Slope Toe

Fig. 8 Pin Field 1, Rilled slope, 46°

Non-Rilled Slope

Bluff Top

	A	B	C	D	E
Row 3	.	.	.	.	.
Row 2	.	.	.	.	.
Row 1	.	.	.	.	.

Slope Toe

Fig. 9 Pin Field 2, Non-rilled slope, 63°

An erosion rate maybe calculated from the pin data as:

$$E.R. = \frac{(L_{1avg} - L_{2avg})}{t} \qquad (3)$$

where: L_{1avg} = Average amount of pin exposure at time 1
L_{2avg} = Average amount of pin exposure at time 2
t = time between measurements

Two additional pin field sites were established approximately 20 km north of the CCSP site to examine the

effects of varying material type on erosion rates. Attributes of all four sites are given in Table 2. Pin Fields 1 and 2 were used to examine the effects of varying slope angle while Pin Fields 2, 3 and 4 examine variations in material type and temperature, respectively. Moisture content and air temperature were relatively constant among the four sites for any given day. Variations in the surface temperature were measured by the relative difference in exposure to solar radiation.

Pin Field Number	Location	Rilled/ Non-rilled	Exposure	Material	Slope Angle (Degree)
1	CCSP	Rilled	Bare	Silty-Clay	46
2	CCSP	N/rilled	Bare	Silty-Clay	63
3	Jett Boundary	N/rilled	Bare	Clayey-Silt	63
4	Ivy	N/rilled	Shielded from sun by vine cover	Clayey-Silt	63

Table 2 Pin Field Attributes

Results of measurements for all the pin fields are provided in Figures 10, 11, 12, and 13. The graphs in these figures show the cumulative exposure for each pin in the pin field. The average value for each date is connected by a line so that a trend is discernible. A value less than zero denotes aggradation of material on the slope or expansion of the surface material from ice activity. Note that slope recession was much more rapid on the 63° slope than the 46° slope. Increased rates of recession were also observed when varying material type and amount of exposure to direct sunlight.

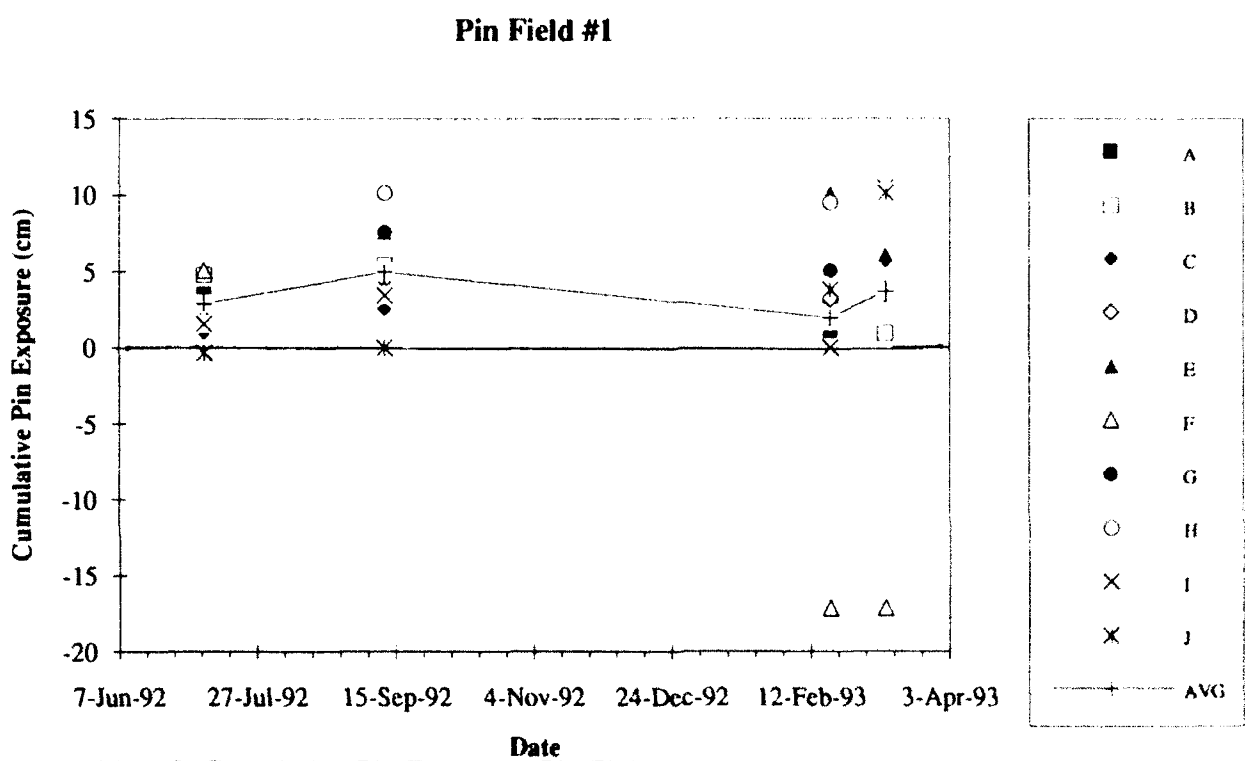


Fig. 10 Cumulative Pin Exposure, Pin Field #1

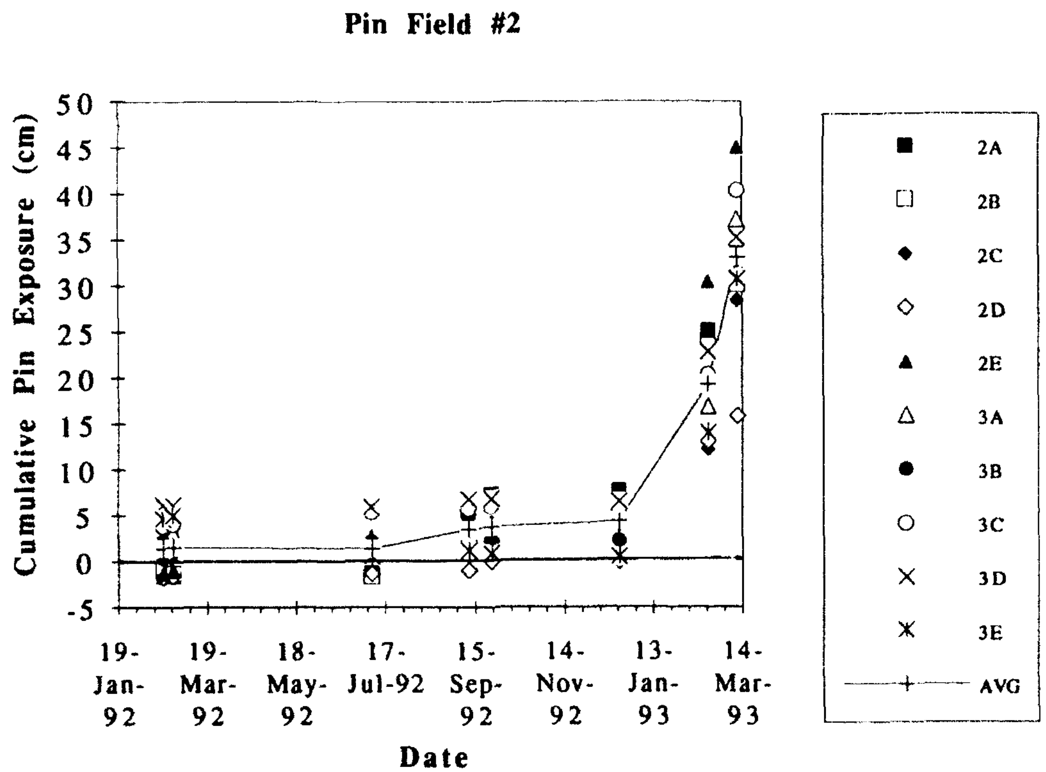


Fig. 11 Cumulative Pin Exposure, Pin Field #2

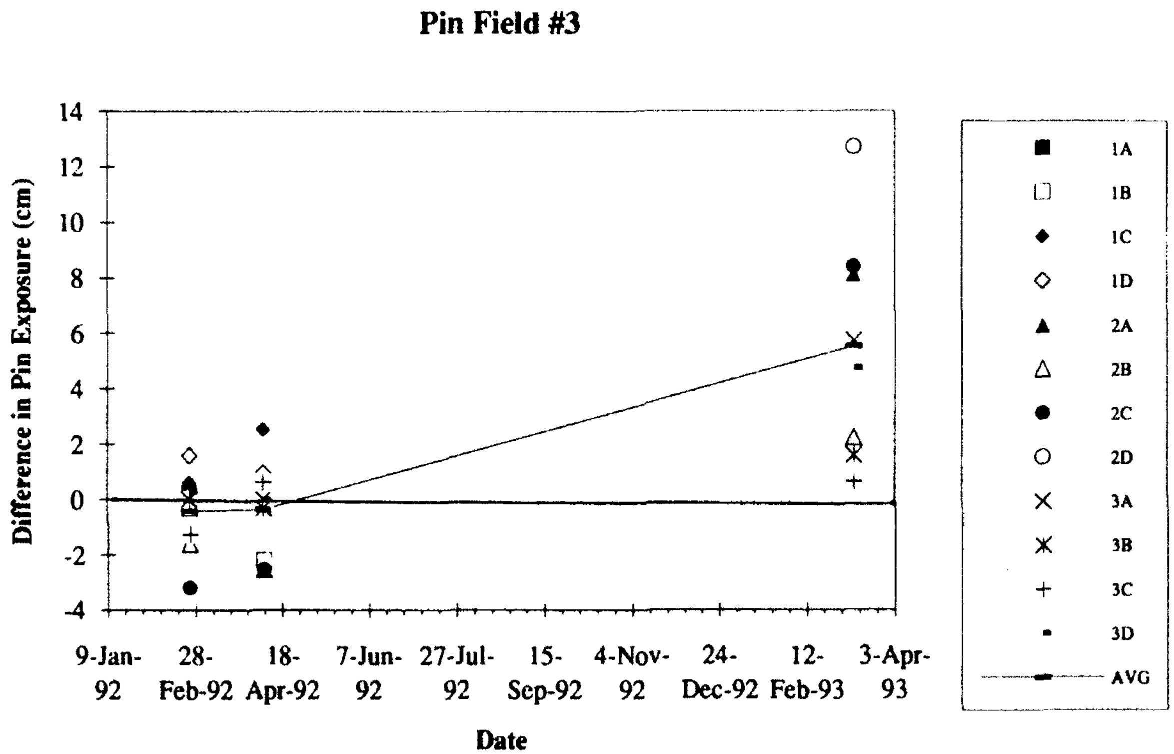


Fig. 12 Cumulative Pin Exposure, Pin Field #3

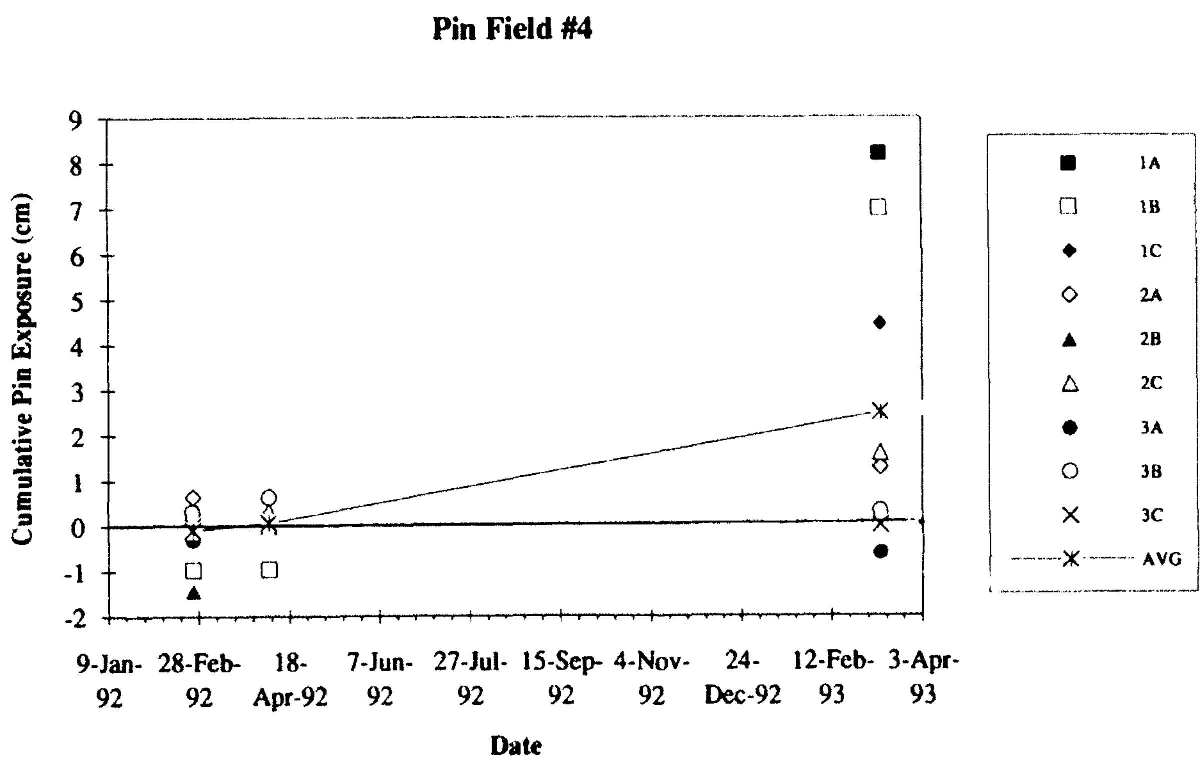


Fig. 13 Cumulative Pin Exposure, Pin Field #4

Because slope recession is a function of precipitation, slope angle, and temperature, Figure 14 provides a means of relating rainfall and temperature activity with the cumulative recession rates of both the 46° and 63° slopes. Significant increases in recession rates can be observed during the winter months. Minimum temperature is provided for only months when freeze-thaw activity is likely. Minimum temperature is used since freezing of the surface moisture is required for the erosion process to begin. Several consecutive days with freezing temperatures are likely to result in freeze-thaw erosion.

2.5 Long Term Recession Rates

Aerial photos from 1938, 1944, 1952, 1971, and 1990 were examined to measure the recession rate of the bluff top at the CCSP study site. Assuming that the slope geometry did not change much over the entire period, bluff top recession can be used as a surrogate for overall slope recession. Recession measurements were made only for sites where the slope profile did not appear to change in the aerial photo. Ground measurements were made between features appearing on all five sets of photos so that scaling between the photos was possible. It was possible to precisely locate the position of the erosion pins only on the 63° slope throughout all five sets of photos. From 1938 to 1944, the bluff top at Pin Field 1 receded at a rate of 0.25 m/yr. After 1944, there was no

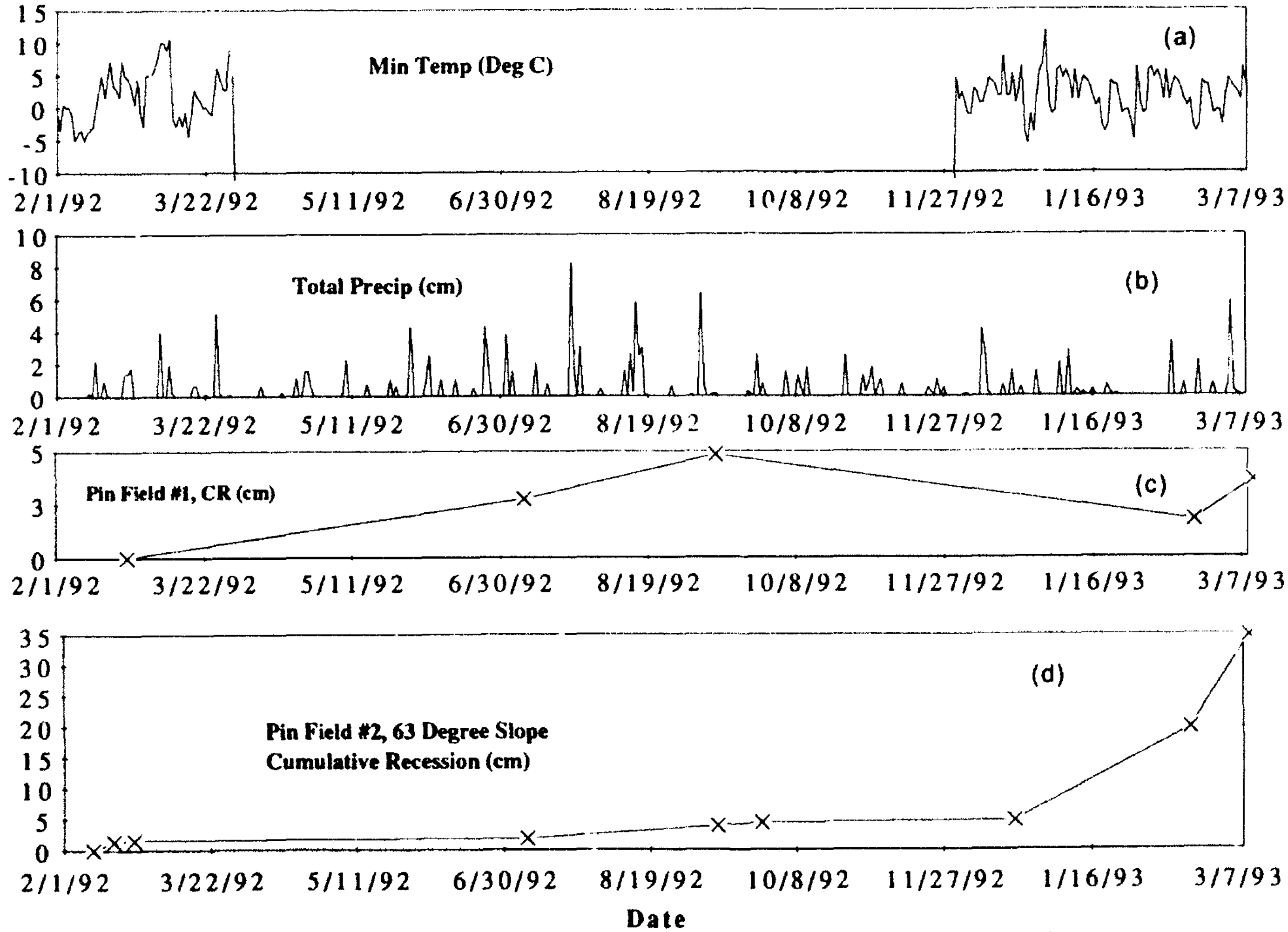


Fig.14 Cumulative Pin Exposure Pin Field 1 and 2; (a) Minimum Temperature (Deg C) from PNAS; (b) Total Daily Precipitation from PNAS; (c) Cumulative Recession, Pin Field 1; (d) Cumulative Recession, Pin Field 2

measurable recession at this location. The recession rates measured for Pin Field 2 are greater by a factor of three (Table 3).

Year	Retreat (m)	Time Span (years)	Rate (m/yr)
1938-52	11.5	14.18	0.8
1952-71	14.5	19.4	0.7
1971-90	18.4	12.1	0.7

Table 3 Bluff Top Recession Rates From Stereo Photos, Pin Field 2 (Miller, 1993).

3. Discussion

3.1 Dominant Erosion Mechanism

Very little slope recession was observed on the 63^{o} slope (Pin Field 2) during the summer months (Fig. 11). The average slope recession rate calculated from pin data during this period was 1.2 cm/month. During winter months, the average slope recession rate increased to 13.0 cm/month. The overall recession rate during the period of observations was 0.3 m/yr, 97% of which occurred during periods of freeze-thaw. Increased erosion rate during the winter months cannot be attributed to overland flow alone because there was no increase in the frequency or amount of rainfall during this period. It is likely, however, that the combination of freeze-thaw activity and overland flow produced most of the observed slope recession. During February 1992, seven freeze-thaw cycles

were observed on consecutive days with no increase in pin exposure. However, a progressive change developed in the appearance of the surface material. The fracture pattern typical of the slope face became more dense and ice crystals were observed to a depth of 5 cm. The upper 1 cm of the slope face was granular and had very low cohesion. Strong winds were capable of eroding some of this granular material from the slope face. Immediately following a rainstorm, there was measurable exposure on the pins and the weathered surface was removed, leaving behind a "fresh" slope face for the process to begin over again. An important observation is that, even for slopes as steep as 63°, transport due to freeze-thaw alone is much less than that resulting from a combination of freeze-thaw and overland flow.

Observations made at Pin Field 1 were considerably different than those made at Pin Field 2. An analysis of the individual pins shows that both erosion and aggradation occurred. Although some net erosion is evident between February 1992 and June 1992, further average changes in slope position are not detectable within the scatter of the individual pin observations. This analysis indicates that some net erosion occured at Pin Field 1, but the recession rate was small during the study period. During that period, the slope may be close to a balance between erosion and aggradation.

Observations indicate that there was at least equal "preparation" of both the 46° and 63° slope from freeze-thaw. Both slopes accumulated a thin layer of this granular weathered surface during freeze-thaw episodes which was removed during a rainfall event. The difference in recession rates may be attributed to the removal of some of the fractured material beneath this granular layer on the 63° slope. After a rainstorm, there was little evidence of a fractured surface on the 63° slope. This same fractured surface was not apparent on the shallow slope where there was a much thicker layer of accumulated material.

Material may be transported by the combination of freeze-thaw and overland flow off the shallow slope at a much slower rate than the steeper slope. The granular material is being eroded equally, but more of the slope material under this granular layer is being removed on the 63° slope than on the 46° slope. If there is a difference between the transport rate and the rate of weathering, or "preparation" of the surface material, there will be accumulation of weathered material at the surface. This probably accounts for the thick layer of weathered material comprising the interrill area on the 46° slope.

Because slope angle varied between Pin Fields 1 and 2 while other factors that might control erosion were constant, it is clear that a change in slope angle results in a dramatic change of erosion rates (Fig. 14). Similar findings are observed in other environments where freeze-thaw is active (Washburn, 1980).

During freeze-thaw, soil particles are carried perpendicularly away from the slope when there is ice crystal growth. When the ice melts, particles are dropped downslope until particle to particle contact is regained. If the slope angle is less than some threshold angle, then the particle moves down slope at a rate which is a function of the slope angle. This threshold angle is defined as the point at which the force of gravity is able to deliver material immediately off the slope surface. From direct observations, both the 63° and 46° slopes of this study are less than this threshold angle and material is delivered away from the slope at much slower rate on the 46° slope.

It was not possible to measure erosion due to freeze-thaw with the pans because continuous contact with the slope face could not be maintained during freeze-thaw episodes. Because freeze-thaw is not active in the summer, it is possible to compare erosion rates measured by pans and pins during the period of predominantly overland flow erosion. Cumulative recession rates as measured by the pins and pans for both slopes during the summer months are given in Table 4. Recession rates from pan observations were computed by converting the weight of the sediment yield in each pan to an *in situ* volume (using dry bulk density) and then dividing it by the contributing drainage area. For the non-rilled portion of the slope, drainage area is estimated as the width of the pan by the length of the slope above the pan. The drainage area for individual rill was directly estimated in the field.

The recession rate measured by these two techniques vary considerably. Some of this difference may be attributed to the strong rainfall events between 8 July and 27 July and 27 August and 11 September when there were no pan measurements. During these time periods, there were 16 rainfall events, two of them quite large (24 July-3.24 inches and 6 September-3.55 inches). Another factor is that the contributing drainage area was estimated differently for the rilled and non-rilled cases. Finally, direct observations reveal that sediment transport varied strongly across the slope. Far more pin observations were made and it is likely that the larger sample number from pin observations provides a better estimate of the spatially variable erosion rate.

	Pan 46°	Pin 46°	Pan 63°	Pin 63°
Dates:	27 Jul-27 Aug	08 Jul-11 Sep	27 Jul-27 Aug	08 Jul-11 Sep
Duration (Days):	32	63	32	63
Recession(cm):	0.413	2.12	0.184	2.03
Recession Rate (cm/day):	0.0129	0.0337	0.00575	0.0322

Table 4 Cumulative Recession and Rates During the Summer, 1992.

3.2 Controls on Surficial Slope Erosion

Experiments were conducted in order to examine the effects of varying different controls on erosion rates due to both freeze-thaw and overland flow. Each experiment is discussed separately below.

3.2.1 Amount of Vegetation

Surface vegetation can act to moderate temperature fluctuations at the slope surface and decrease the frequency of freeze-thaw cycles. Direct solar radiation is capable of thawing the surface even while ambient air temperatures remain well below freezing. A heavy vegetative cover could reduce the recession rates by protecting the slopes from direct sunlight.

The effect of vegetation on freeze-thaw can be investigated by comparing erosion at Pin Fields 3 and 4. The significant difference in controls between the two sites was that Pin Field 4 had heavy vine cover which draped over the entire slope face, protecting it from direct sunlight. The difference in cumulative recession between Pin Field 4 and Pin Field 3 demonstrates the lower recession rate observed on the slope face with greater protection (Figs. 12 and 13). During the winter months, ice was observed on the slope face under the vine cover when it was not observed at any of the other sites. This indicates that the difference in recession rates between the pin fields may be due to Pin Field 3 being subjected to more freeze-thaw cycles than Pin Field 4.

3.2.2 Material Properties

Comparison among all four pin fields provides the opportunity to investigate the effect on slope erosion of varying material type and temperature. The cumulative recession rates of all four sites are shown on Figure 15. Material type has an influence on slope recession rates because it defines the amount of void space potentially filled by water. It also influences the hydraulic conductivity of the material necessary to feed growing ice crystals. Often, fine grain materials, such as clay-rich deposits, have a very low permeability which can limit the flux of water to the zone of freezing (Walder and Hallet, 1985). Since the stratigraphic unit at Pin Fields 1 and 2 has a significant clay fraction, the hydraulic conductivity is very low. A bale test was conducted on a nearby groundwater well and a hydraulic conductivity of 10^{-7} m/s was computed for the same stratum using the Horslov formula (Freeze and Cherry, 1979). The conductivity of the highly weathered, fractured surface is likely to be much higher and groundwater is readily transmitted to growing ice crystals along this upper boundary. Similar observations of shallow subsurface flow have been made by Dunne (1990).

Comparison of the slope erosion at Pin Fields 2 and 3 demonstrates the effects of varying material type on erosion rates due to freeze-thaw (Fig. 15). The bed material in Pin Field 3 consists mostly of silt and fine sand with only a small percentage of clays while the material at Pin Field 2 is 44% clay.

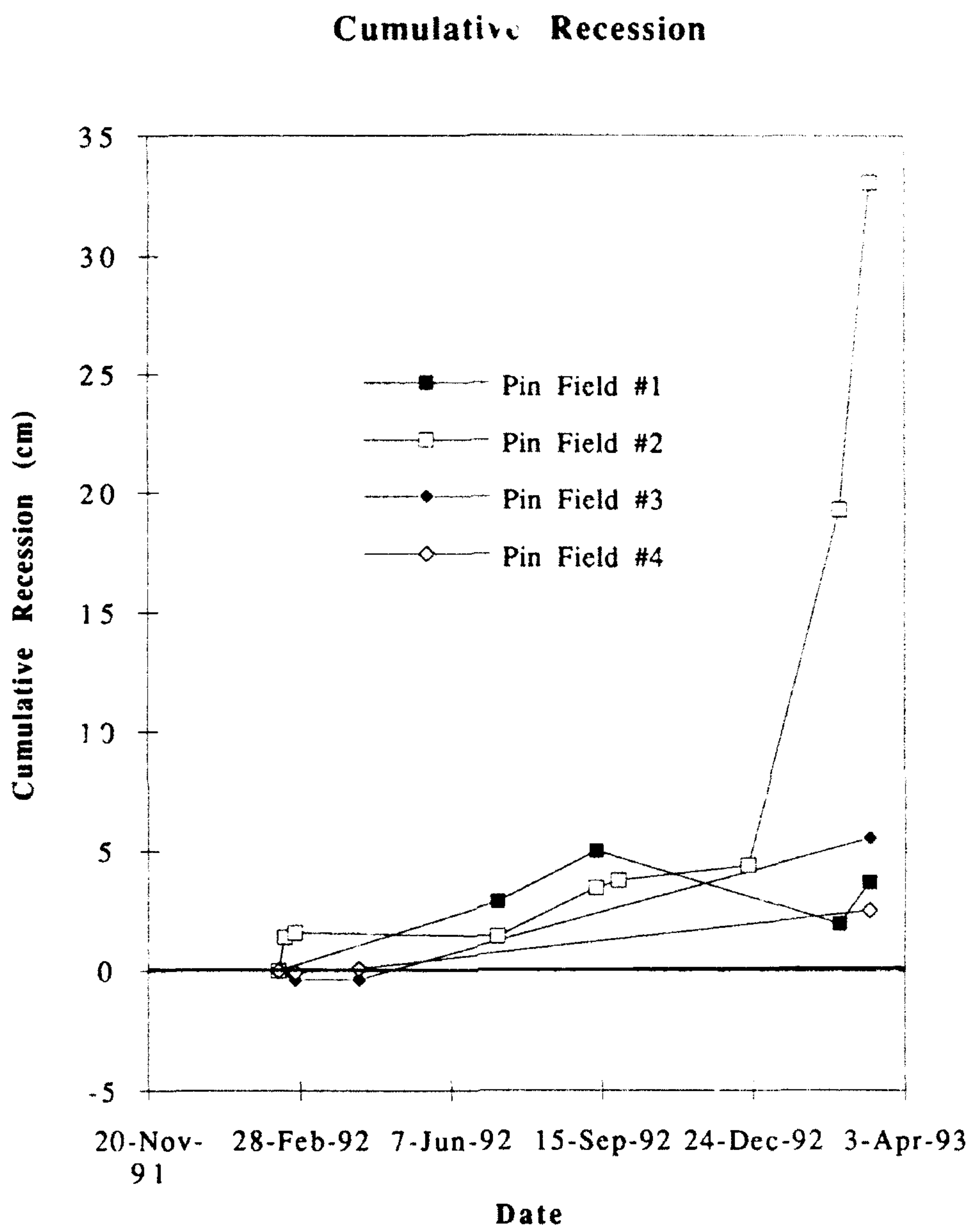


Fig. 15 Cumulative Recession, All Four Pin Fields

Over the course of the year, both sites were exposed to similar environmental controls. Amount of precipitation, time length of exposure to freezing and thawing, temperatures, and slope angle were relatively constant. The cumulative recession rate at Pin Field 3 was 6 cm over 13 months compared with the 33 cm observed at Pin Field 2 during the same time period. Measurements were not made at the beginning of the winter at Pin Field 3 so it is difficult to directly compare the amounts of erosion during the winter months. Regardless, the overall recession rate is considerably less than at Pin Field 2 and this difference may be attributed to the difference in material. Clay-rich material, if saturated, is more susceptible to freeze-thaw action than coarser grain material. Most of the expansion due to freezing water is translated directly into the separation of particles since there is relatively little void space. Also, during the thaw, the clay grains do not necessarily reorient as parallel sheets which reduces material cohesion.

3.2.3 Sediment Yield and Slope Angle

Pans were located on the non-rilled portion of both the 46° and 63° slopes. Slope height above the pans, material type, and rainfall were identical for all pans. The average sediment yield for each pan and 8 rainstorm events is shown in Figure 16. Also shown is the total sediment yield collected in the pans on a continuous basis after 25 September until 21 December. There is a consistently greater amount of sediment yield on the

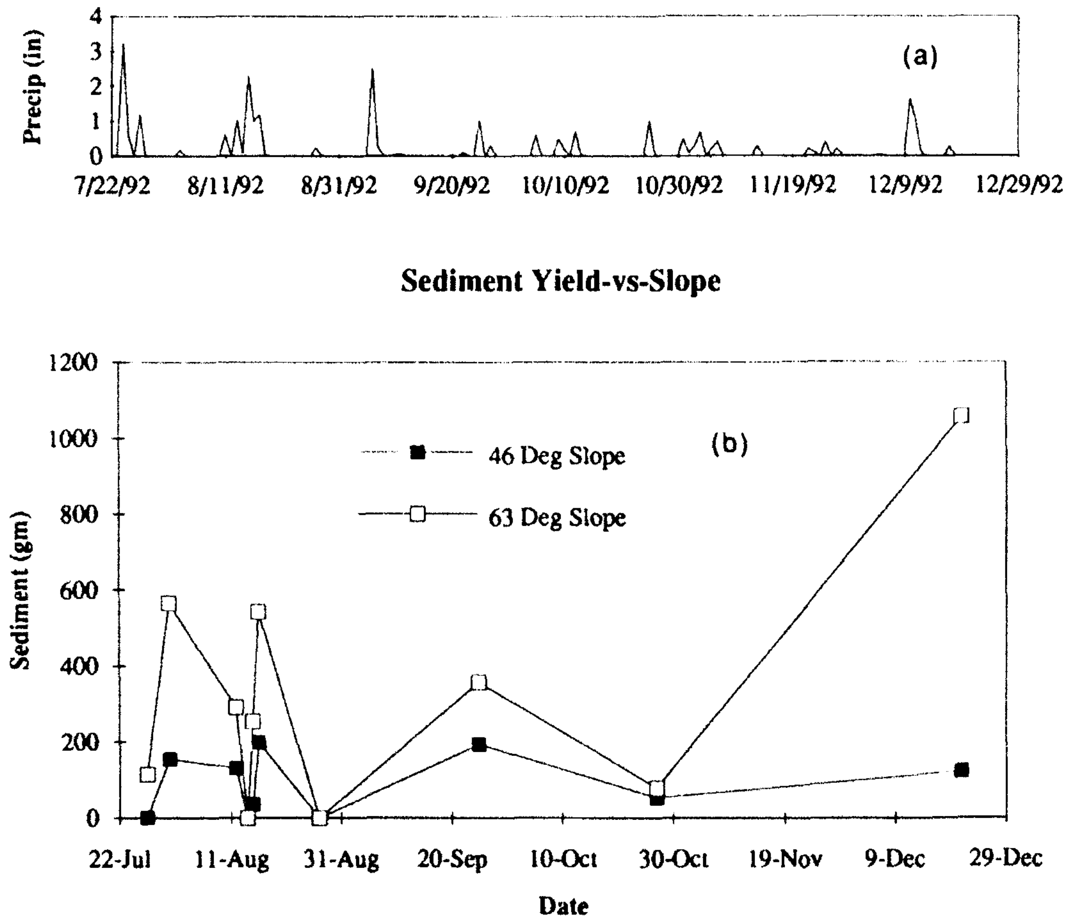


Fig 16 Sediment Yield as a Function of Slope Angle with Cimate Data
(a) Total Daily Precipitation from PNAS; (b) Sediment Yield as a Function of Slope angle

steeper slope. This shows that sediment discharge is a function of slope angle, a point common to many other experiments (Dunne and Aubrey, 1986; Mathier et al, 1989).

An important observation is that there were two rainstorm events for which there was no sediment discharge on either slope. These rainstorms had a peak rainfall intensity of 0.16 in/hr (14 August) and 0.12 in/hr (27 August) measured at the Patuxent Naval Air Station (PNAS). Rainfall intensity values suggest that an intensity of at least 0.16 in/hr is needed to initiate slope erosion on the non-rilled portion of both the 46° and 63° slopes.

It is also evident in Figure 16 that less sediment was eroded from the slopes during the time between 25 September and 21 December than during the same length of time during the summer months. From the data provided by PNAS, there were 20 days in which rain fell between 27 July and 25 September for a total precipitation of 10.85 inches. Similarly, there were 25 days in which rain fell between 26 September and 21 December for a total precipitation of 10.43 inches. Despite not collecting the yield from an intense rainstorm (3 September), there was approximately twice as much sediment shed from the slopes during the summer than autumn months. This is significant because it suggests that most of the erosion due to overland flow is attributable to the more intense rainstorms of the summer months than during the Fall. In his work on Baisman Run in Baltimore County, Maryland, Wolman (1993) noted that 85% of the total annual sediment yield was

85% of the total annual sediment yield was associated with seven to eight rainstorm events in the late summer months.

3.2.4 Sediment Yield From Rilled and Non-Rilled Slopes

The pan installation on the 46° slope included one intersecting a rill and another on a smooth portion of the hillslope. All other controls were constant and sediment yield was examined for the same storm events and time frame as the first experiment. The sediment yield measured in each pan is given in Figure 17. As with the first experiment, several important observations can be made from this simple graph.

The most striking difference is that the sediment yield from the rill is seven to 15 times greater than that from the non-rilled slope. The greater sediment yield from the rill may be attributed to an increase in both the size of the contributing drainage area and the shear stress caused by concentrated flow in the rill channel.

Many other studies support this increase in sediment discharge in rilled channels. Mutchler and Young (1975) showed that over 80% of sediment is transported in rills while Meyer et al (1975) reported a threefold increase in soil loss after rill development. Similarly, Morgan (1977) found that rilled sediment transport exceeded non-rilled transport by a factor of 40 on 11° slopes.

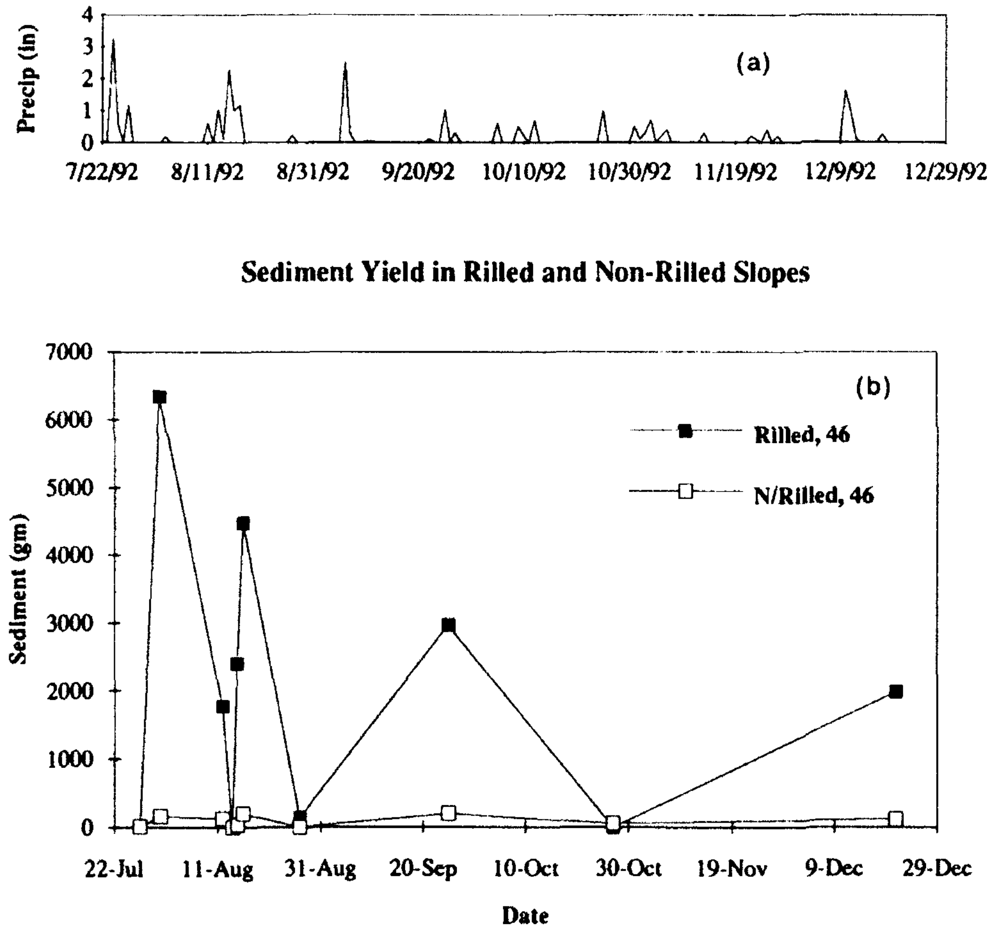


Figure 17 Sediment Yield as a Function of Rilling with Climate Data
(a) Total Daily Precipitation from PNAS; (b) Sediment Yield as a Function of Rill or Non-Ril

Julien and Simons (1985) provides a general relationship between sediment discharge and the dominant controls.

$$q_s = \alpha\, S^{\beta} q^{\gamma} i^{\delta} \qquad (4)$$

Where: q_s = Sediment Discharge

α = Constant

S = Slope Gradient

q = Flux of Overland Flow

i = Rainfall Intensity

Typical values of γ are between 1.0 and 2.0. Figure 18 is a comparison of sediment yield in the rilled and non-rilled portions of the slope using the few cases where both values (q and qs) were measured. The slopes of both lines provide a γ value of 1.7 to 2.2 , with the non-rilled values at a steeper slope. The difference in q_s between these two sets of points is attributed to the difference in contributing drainage areas and the difference in flow strength due to channeled flow. Measurements of the contributing drainage area were made for both portions of the slope (the rill drainage area was 2.5 times that of the non-rilled). Figure 19 shows the results of dividing the sediment yield from both portions of the slope by the contributing drainage area. There is a 10 fold decrease in the q_s value for the rilled slope. The remaining difference may be related to the increase in shear stress associated with channeled flow compared to sheet flow. This comparison of the two

figures indicates that most of this difference in sediment transport is due to the difference in the size of the drainage areas.

The rilled slope can also transport sediment at a lower rainfall intensity. On 27 August, sediment was transported on the rilled portion of the slope and not on the non-rilled portion. The rainfall intensity on this day was 0.16 in/hr and was capable of removing 135 gm of sediment from the rilled portion of the slope. This suggests that a sediment transport threshold between rilled and non-rilled slopes is roughly 0.16 in/hr.

Rilled channels tend to deliver sediment less predictably than with sheetflow. The storm event on 25 September (0.16 in/hr over 8 hours) shed 2963.6 gm of sediment from the rilled channel while the storm event on 15 August (0.24 in/hr over 12 hours) delivered only 2394.3 gm of sediment. The longer, more intense storm event should have produced a greater amount of sediment transport. Field observations suggest that the quantity of sediment yield may be affected by bank failures along the rill channel. Other studies have shown similar variance. Slatery and Bryan (1991) noted similar variations and observed that bank collapse is not entirely a function of storm intensity or overland flow but is controlled by many other factors, as well.

Poesen (1984) discovered a wide variance in the amount of overland flow (q) captured from similar rills during repetitive rainfall events. Overland flow was found to vary widely, even for similar rill geometry and material properties.

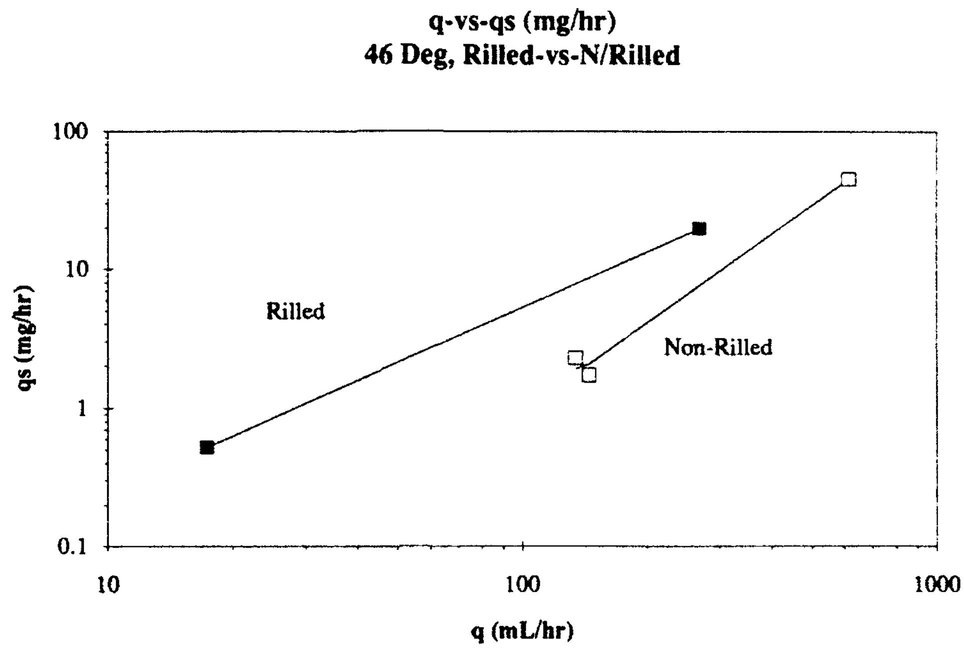


Fig 18 Comparison of sediment flux from rilled and non-rilled slope

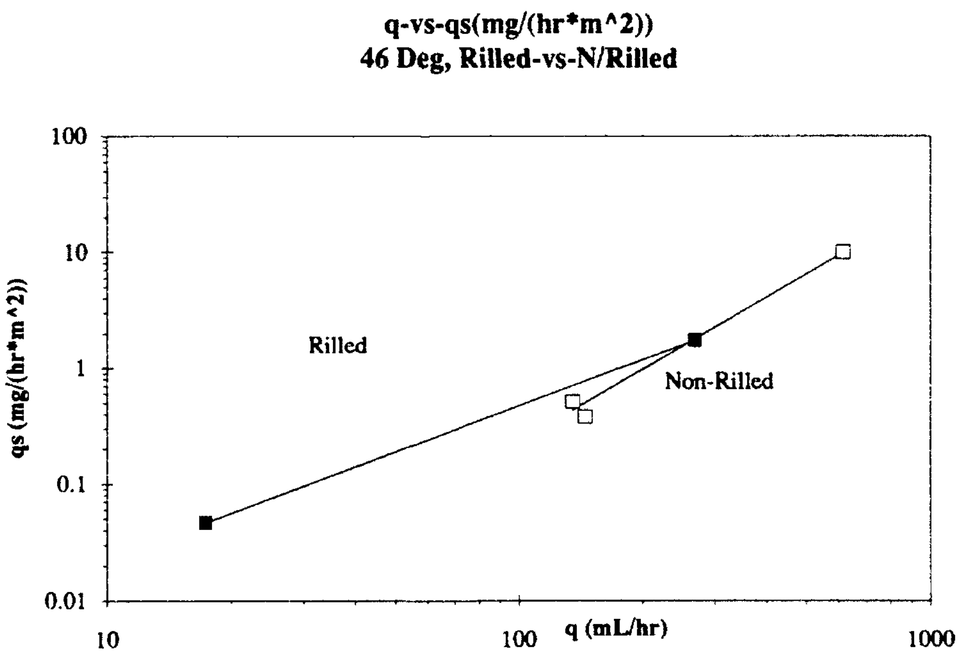


Fig 19 Comparison of sediment flux (mg/(hr*m^2)) from rilled and non-rilled slope

Poesen attributes this variance to large changes in infiltration rates along the rill boundary which cause q to change as it moves down the rill. A change in q should, in turn, directly effect sediment discharge.

The amount of overland flow as a function of rainfall intensity or total rainfall is also likely to vary. The length of the time between storm events determines, in part, the amount of surficial weathering, or thickness of this "prepared" layer. Before the initiation of overland flow, precipitation infiltrates the soil and is transmitted, in part, through this shallow weathered surface. The longer the time period between storm events, the deeper this prepared layer extends below the surface, thereby increasing the proportion of precipitation transmitted as shallow sub-surface flow.

3.3 Observed versus Long Term Recession Rates

The recession rates observed during this study can be compared with the long term recession rate measured in aerial photos from 1938 to 1990. From the stereo photos, the slope recession rate on the 63^{o} slope was 0.7 m/yr (between 1938 and 1990). The average pin recession rate measured at Pin Field 2 was 33 cm from February 1992 to March 1993, or 0.30 m/yr. On the 46^{o} slope, the observed recession rate (aerial photos) between 1938 and 1944 was 0.25 m/yr. Since 1944, there has been no measurable difference in the location of the

bluff top. Correspondingly, the pin measurements made on the 46° slope indicate a recession rate of 0.022 m/yr.

Comparison of rates from the separate techniques supports two important points. The rate of erosion measured by the pins and stereo photos are comparable for both slopes. Second, the gentler slope has been, and is currently, receding at a much slower rate than the steeper slope since 1944. From the aerial photos, there was a decrease in the bluff top recession rates around 1944. This might result from toe protection provided by ironstone blocks that have fallen from upslope. Prior to 1944, the slopes were presumably at the same angle and receding at similar rates. Once the ironstone blocks fell to the slope toe, the recession of the slope toe was significantly reduced. However, surface processes continued to act along the slope surface and caused the bluff top to recede at a rate greater than the slope toe. This net difference in recession rates between the bluff top and slope toe caused a reduction in the slope angle. As the slope angle decreases, there is a decrease in the erosion rate.

The difference in erosion rate is also confirmed by an examination of the shore profile. In 1938, the shore profile was relatively straight. After 1944, a point gradually develops along the base of the 46° slope. These erosion rates are likely to be cyclic. Prior to the development of toe protection, the shoreline appeared relatively straight, indicating similar erosion

rates along the entire slope face. From 1944 until present, the recession rates have differed, as indicated by the development of this point. Eventually, the ironstone blocks will disappear and the slope recession rates will readjust so that the shoreline will straighten out with time. Once the ironstone blocks are gone, the slope at the prominent point will be subject to increased wave action and recede at a rate faster than the surrounding shoreline.

There was some difference in erosion rates on the 63° slope as measured by pin and photo data (0.7 m/yr by photo, 0.3 m/yr by pin). A possible explanation for the difference might be that the recessions rates were measured over two widely varying time frames. The recession rates measured from the stereo photos are an average rate measured over a period of 52 years whereas the pin data covers 13 months.

4. Conclusions

Surface erosion was observed over a 13 month period along steep 46° and 63° segments of coastal slopes in the Calvert Cliffs State Park. Erosion resulting from the combination of freeze-thaw and overland flow is the dominant mechanism acting on the steeper slopes at the experiment site. Erosion by this process accounts for 93% of the overall slope recession with rates of 15 cm/month acting during the winter period. Recession rates due to overland flow alone are much less, with maximum observable values of 2.0 cm/month. Most of the

overland flow erosion occurs during intense summer storms. During the winter, the combination of freeze-thaw and rainfall cause the greatest amount of slope recession.

On the gentler slopes, the overall erosion rate is lower and the suite of erosion mechanisms is different. The recession rate is very small and it appears that the slope is close to a steady state with rates of erosion and rates of deposition being approximately equal.

An analysis of aerial photos dating back to 1938 confirms that both slopes are eroding at different rates. The observed values during this 13 month period were slightly less than those measured from the stereo photos and this may be attributable, in part, to less severe climatic conditions than average. With relatively strong agreement between the observations made from both the pin and photo data, it is likely that erosion will continue at similar rates for the near future.

Erosion due to freeze-thaw and overland flow is influenced by a variety of controls. Changes in slope angle were found to have a significant effect on erosion rates. The 63° slope receded 0.33 m over the 13 month observation period while recession was so slight on the 46° slope recession was so slight it was not detectable using erosion pins. A vegetative cover influences erosion rates by reducing the number of freeze-thaw cycles. Erosion rates were twice as great on unprotected slopes as on slopes that were covered with vegetation. A change in material properties also influences slope erosion rates due to freeze-thaw. Clay-rich

material, if saturated, is more susceptible to the effects of freeze-thaw than coarser material. Finally, observations made during the summer months, when erosion by overland flow was dominant, reveal that sediment yield along rilled portions of the slope were seven to 15 times greater than along non-rilled portions of the slope. This increase in sediment yield is attributed to the increase in the size of the drainage area and the increase in shear stress associated with channelized flow.

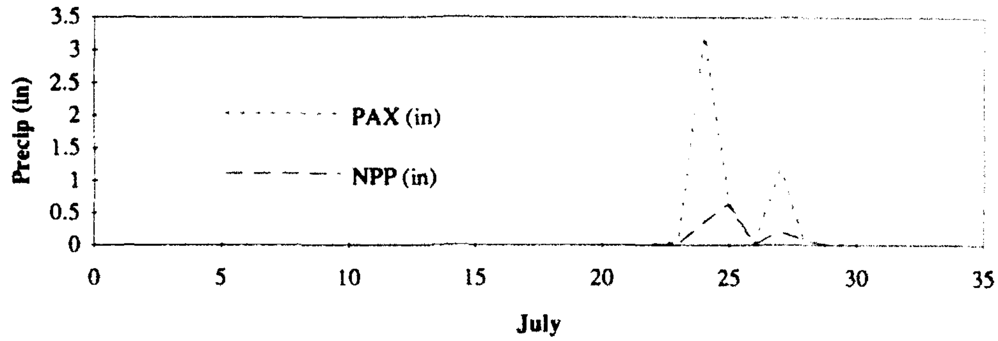
In comparison with other erosion mechanisms (deep and shallow landslides), the analysis of aerial photos reveals that bluff top recession rates along slopes with active subsurface erosion mechanisms are comparable to bluff top recession rates on slopes dominated by surface mechanisms. Examination of four sites where subsurface processes clearly dominate show a range of recession rates of 0.1 to 5.8 m/yr with three out of the four averaging 0.5 m/yr.

Appendix A, Table 1

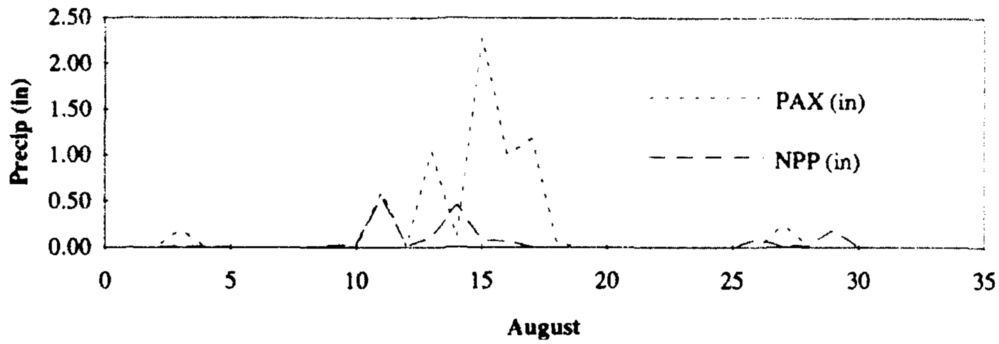
Date	Pan#	Rilled?*	Slope Angle (Degree)	Sed Mass (g)	Storm Duration (hours)	Volume H2O (mL)	Total Precip PAX (in)	Peak PAX (in/hr)	Peak NPP (in/hr)	Total Precip NPP (in)
27-Jul	1	nr	60	115	6	956.49	1.19	0.24		
	2	nr	60	126.7	6	3022.18	1.19	0.24		
	4	r	40	10.28	6	872.12	1.19	0.24		
	5	r	40	13.81	6	810.79	1.19	0.24		
	6	nr	40	3.12	6	103.82	1.19	0.24		
31-Jul	1	nr	60	596.6						
	2	nr	60	5483.3						
	3	nr	60	535						
	4	r	40	6340.6						
	5	r	40	1790.2						
	6	nr	40	155.6		2155.28				
12-Aug	1	nr	60	666.9	4		0.6	0.2	0.25	0.54
	3	nr	60	111.7	4		0.6	0.2	0.25	0.54
	4	r	40	1783.8	4		0.6	0.2	0.25	0.54
	6	nr	40	131.85	4		0.6	0.2	0.25	0.54
	7	nr	60	56.53	4		0.6	0.2	0.25	0.54
	8	nr	60	182.2	4		0.6	0.2	0.25	0.54
	9	nr	60	240.1	4		0.6	0.2	0.25	0.54
	10	nr	60	147	4		0.6	0.2	0.25	0.54
	11	nr	60	238.3	4		0.6	0.2	0.25	0.54
14-Aug	1	nr	60	0	6	3580	0.62	0.16	0.04	0.11
	3	nr	60	0	6	2365	0.62	0.16	0.04	0.11
	4	r	40	0	6	4200	0.62	0.16	0.04	0.11
	6	nr	40	0	6	663	0.62	0.16	0.04	0.11
	7	nr/s	60	0	6	1387	0.62	0.16	0.04	0.11
	8	nr/s	60	0	6	408	0.62	0.16	0.04	0.11
	9	nr/s	60	0	6	560	0.62	0.16	0.04	0.11
	10	nr	60	0	6	2150	0.62	0.16	0.04	0.11
	11	nr	60	0	6	3220	0.62	0.16	0.04	0.11
15-Aug	1	nr	60	368.7	12		2.3	0.24	0.01	0.08
	3	nr	60	321	12		2.3	0.24	0.01	0.08
	4	r	40	2394.3	12		2.3	0.24	0.01	0.08
	6	nr	40	35.7	12		2.3	0.24	0.01	0.08
	7	nr/s	60	159.3	12		2.3	0.24	0.01	0.08
	8	nr/s	60	195.3	12		2.3	0.24	0.01	0.08
	9	nr/s	60	307.5	12		2.3	0.24	0.01	0.08
	10	nr	60	153.1	12		2.3	0.24	0.01	0.08
	11	nr	60	172.16	12		2.3	0.24	0.01	0.08
16/17 Aug	1	nr	60	982.6	11		2.2	0.4	0.01	0.06
	3	nr	60	651.9	11		2.2	0.4	0.01	0.06
	4	r	40	4478.4	11		2.2	0.4	0.01	0.06
	6	nr	40	198.7	11		2.2	0.4	0.01	0.06
	7	nr	60	595.7	11		2.2	0.4	0.01	0.06
	8	nr	60	847.2	11		2.2	0.4	0.01	0.06
	9	nr	60	1081.2	11		2.2	0.4	0.01	0.06
	10	nr	60	260.3	11		2.2	0.4	0.01	0.06
	11	nr	60	273.3	11		2.2	0.4	0.01	0.06
27-Aug	1	nr	60	0	3		0.24	0.12	0.16	0.19
	3	nr	60	0	3	1660	0.24	0.12	0.16	0.19
	4	r	40	135.2	3	1849	0.24	0.12	0.16	0.19
	6	nr	40	0	3	418	0.24	0.12	0.16	0.19
	7	nr	60	0	3	2630	0.24	0.12	0.16	0.19
	8	nr	60	0	3	845	0.24	0.12	0.16	0.19
	9	nr	60	0	3	985	0.24	0.12	0.16	0.19
	10	nr	60	0	3	810	0.24	0.12	0.16	0.19
	11	nr	60	0	3	900	0.24	0.12	0.16	0.19
25-Sep	1	nr	60	775.4	8		1	0.16	0.21	0.9
	3	nr	60	257.4	8		1	0.16	0.21	0.9
	4	r	40	2963.6	8		1	0.16	0.21	0.9
	6	nr	40	194	8		1	0.16	0.21	0.9
	7	nr	60	13[illegible]8	8		1	0.16	0.21	0.9
	8	nr	60	453.1	8		1	0.16	0.21	0.9
	9	nr	60	323.8	8		1	0.16	0.21	0.9

Date	Pan#	Rilled?*	Slope Angle (Degree)	Sed Mass (g)	Storm Duration (hours)	Volume H2O (mL)	Total Precip PAX (in)	Peak PAX (in/hr)	Peak NPP (in/hr)	Total Precip NPP (in)
	10	nr	60	189	8		1	0.16	0.21	0.9
	11	nr	60	201.1	8		1	0.16	0.21	0.9
27-Oct	1	missing								
	3	nr	60	66.01						
	4	missing								
	6	nr	40	53						
	7	nr	60	76.48						
	8	nr	60	9.15						
	9	nr	60	64.08						
	10	nr	60	97						
	11	nr	60	69.22						
21-Dec	1	nr	60	1282.9						
	3	nr	60	1884.8						
	4	r	40	1973.1						
	6	nr	40	122.4						
	7	nr	60	676.3						
	8	nr	60	607.5						
	9	nr	60	1198.4						
	10	nr	60	0						
	11	missing								

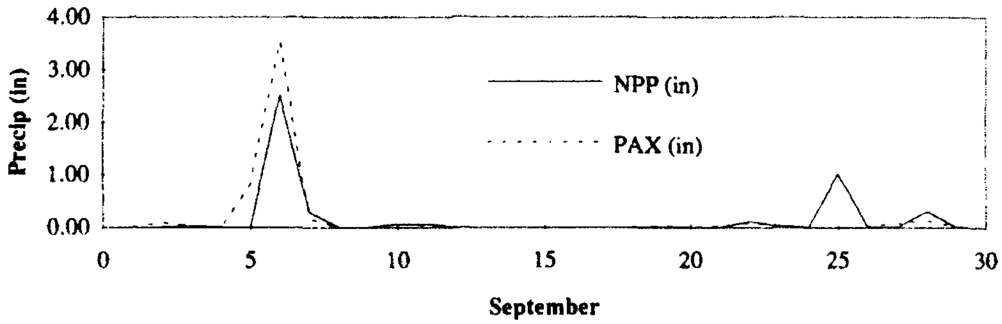
Appendix B



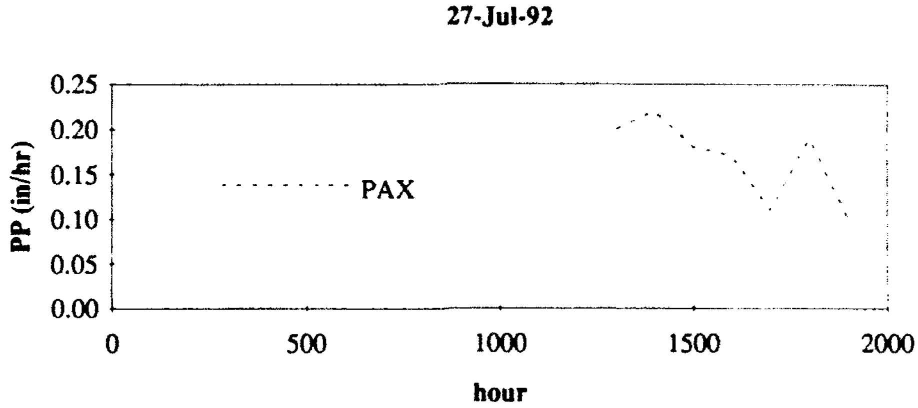
Graph 1 Total Daily Rainfall for Last week in July



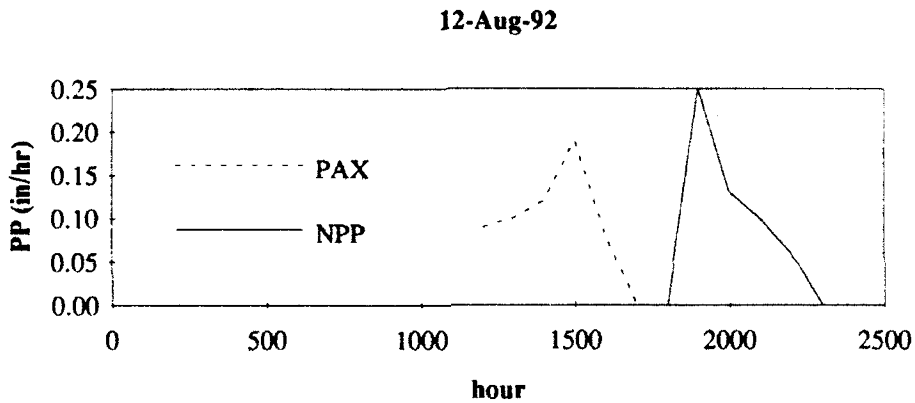
Graph 2 Total Daily Rainfall for August



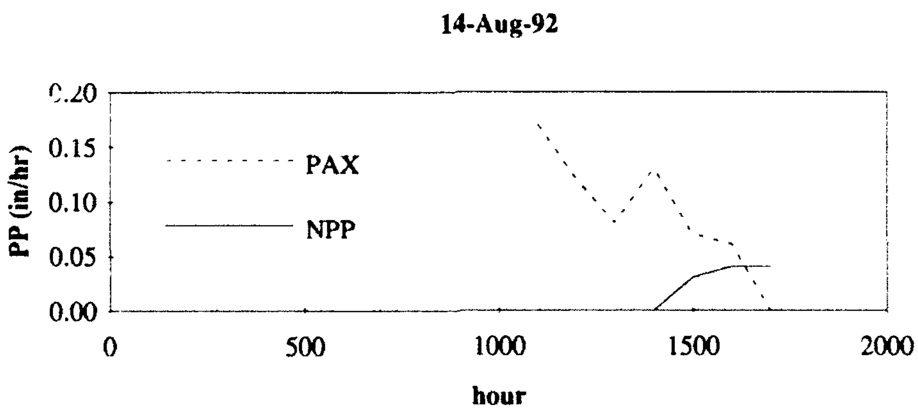
Graph 3 Total Daily Rainfall for September



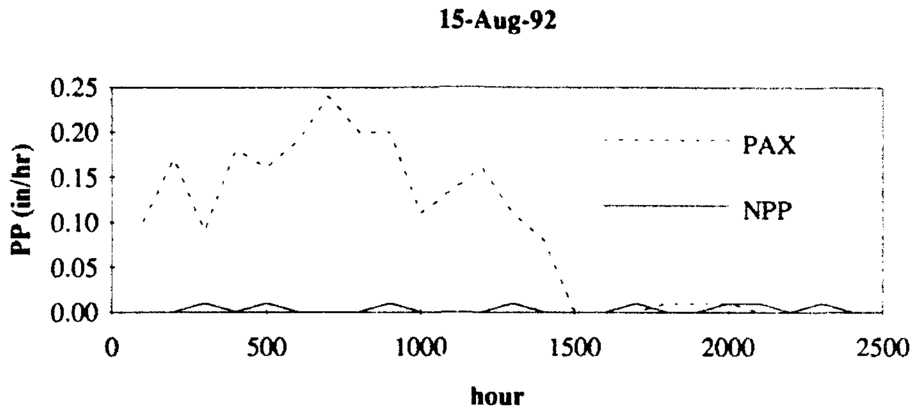
Graph 4 Rainfall intensity PAX, 27 July 1992



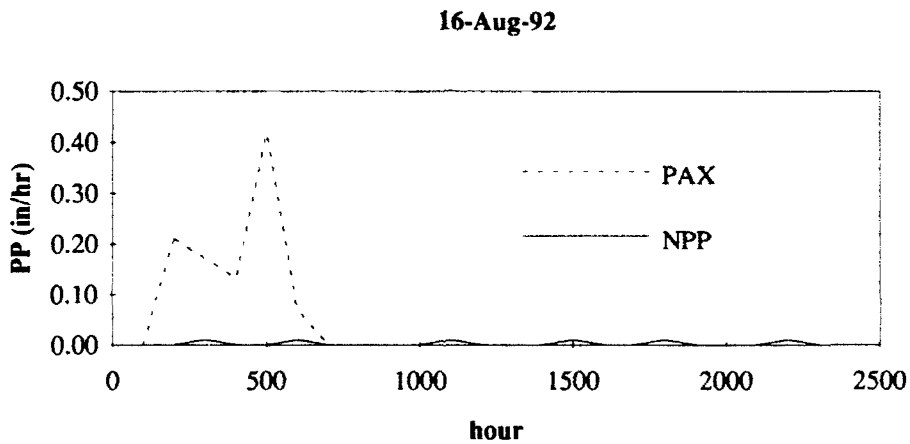
Graph 5 Rainfall intensity PAX and NPP, 12 August 1992



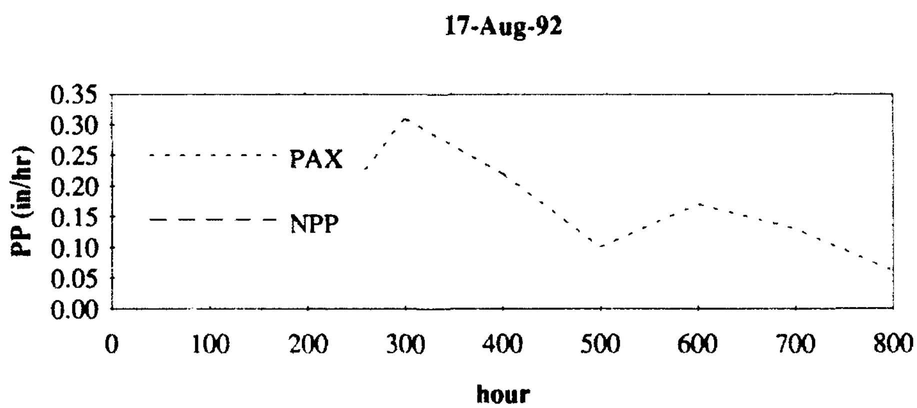
Graph 6 Rainfall intensity PAX and NPP, 14 August 1992



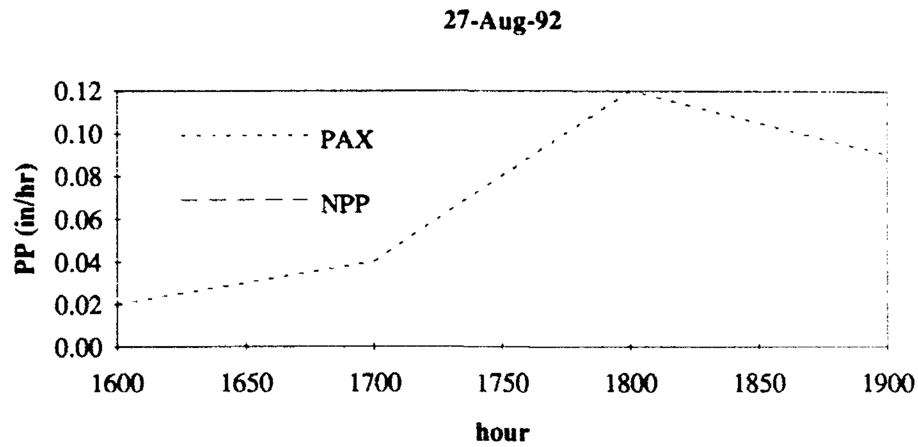
Graph 7 Rainfall intensity PAX and NPP, 15 August 1992



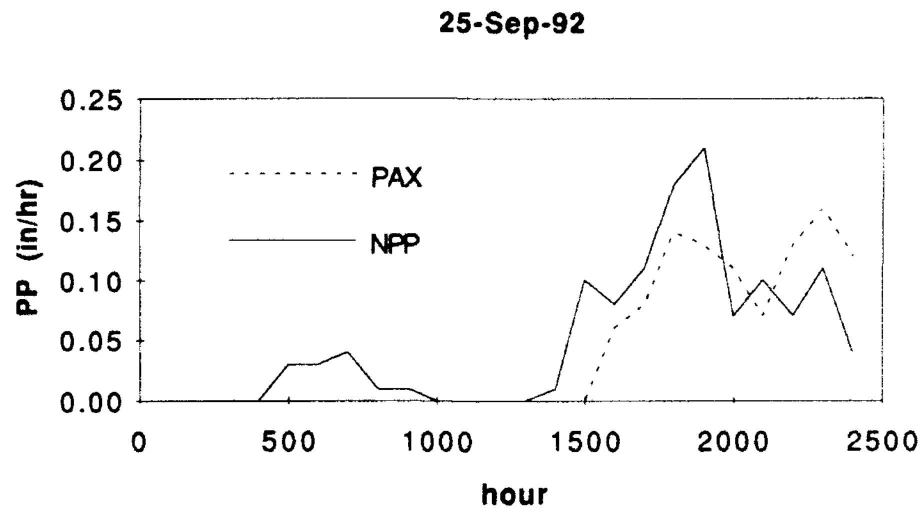
Graph 8 Rainfall intensity PAX and NPP, 16 August 1992



Graph 9 Rainfall intensity PAX and NPP, 17 August 1992



Graph 10 Rainfall intensity PAX and NPP, 27 August 1992



Graph 11 Rainfall intensity PAX and NPP, 25 September 1992

Appendix	C						
Month:	Feb-92			Month:	Mar-92		
Day	Maximum	Minimum	Mean	Day	Maximum	Minimum	Mean
1	40	31	36	1	63	27	45
2	44	26	35	2	66	41	54
3	43	33	38	3	50	41	46
4	53	32	43	4	45	41	43
5	43	32	38	5	51	43	47
6	42	30	36	6	51	46	49
7	35	23	29	7	65	50	58
8	57	25	41	8	67	50	59
9	43	26	35	9	65	48	57
10	35	23	29	10	66	51	59
11	54	25	40	11	61	29	45
12	43	26	35	12	43	27	35
13	33	27	30	13	41	30	36
14	49	32	41	14	47	27	37
15	57	37	47	15	41	31	36
16	58	41	50	16	36	24	30
17	45	35	40	17	66	30	48
18	46	40	43	18	48	37	43
19	57	45	51	19	40	35	38
20	51	38	45	20	45	34	40
21	59	37	48	21	45	32	39
22	56	35	46	22	45	32	39
23	60	45	53	23	43	31	37
24	49	41	45	24	47	30	39
25	43	40	42	25	54	37	46
26	44	37	41	26	52	43	48
27	53	33	43	27	58	40	49
28	61	40	51	28	53	37	45
29	58	31	45	29	58	37	48
				30	68	48	58
				31	57	41	49
Table 1				Table 2			

Month:	Dec-92			Month:	Jan-93		
Day	Maximum	Minimum	Mean	Day	Maximum	Minimum	Mean
1	46	40	43	1	58	33	46
2	50	34	42	2	38	30	34
3	48	36	42	3	44	31	38
4	50	33	42	4	65	42	54
5	45	30	38	5	64	43	54
6	40	30	35	6	48	40	44
7	46	37	42	7	46	42	44
8	41	36	39	8	44	40	42
9	38	33	36	9	39	34	37
10	51	33	42	10	46	42	44
11	51	36	44	11	38	34	36
12	44	40	42	12	45	38	42
13	43	39	41	13	48	40	44
14	42	38	40	14	44	39	42
15	39	35	37	15	42	37	40
16	52	35	44	16	39	34	37
17	60	46	53	17	48	32	40
18	46	35	41	18	42	34	38
19	50	35	43	19	35	27	31
20	52	41	47	20	42	25	34
21	41	33	37	21	47	27	37
22	51	37	44	22	51	39	45
23	53	43	48	23	49	38	44
24	44	25	35	24	66	38	52
25	42	22	32	25	45	34	40
26	43	30	37	26	35	30	33
27	35	25	30	27	45	31	38
28	43	35	39	28	51	31	41
29	48	42	45	29	51	28	40
30	53	44	49	30	48	23	36
31	66	53	60	31	54	43	49
Table 3				Table 4			

Month:	Feb-93			Month:	Mar-93		
Day	Maximum	Minimum	Mean	Day	Maximum	Minimum	Mean
1	48	33	46	1	47	27	37
2	32	30	34	2	61	35	48
3	53	31	38	3	53	40	47
4	48	42	54	4	52	38	45
5	55	43	54	5	50	37	44
6	45	40	44	6	49	36	43
7	33	42	44	7	55	34	45
8	45	40	42	8	60	43	52
9	42	34	37	9	50	38	44
10	54	42	44				
11	53	34	36				
12	40	38	42				
13	41	40	44				
14	43	39	42				
15	43	37	40				
16	56	34	37				
17	47	32	40				
18	36	34	38				
19	27	27	31				
20	40	25	34				
21	44	27	37				
22	66	39	45				
23	41	38	44				
24	36	38	52				
25	31	34	40				
26	34	30	33				
27	36	31	38				
28	37	31	41				
Table 5				Table 6			

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Vitae

Joseph P. Schweitzer was born at Ft. Knox, Kentucky September 7, 1961. He received a bachelor's degree (BS) in Geology from the University of Washington in 1983. He is currently a Captain in the United States Army and will teach at the United States Military Academy upon graduation from The Johns Hopkins University.